THE JOURNAL OF NAVIGATION (2005), **58**, 433–450. © The Royal Institute of Navigation
doi:10.1017/S0373463305003371 Printed in the United Kingdom

The Effect of Helicopter Rotors on GPS Signal Reception

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This paper presents the results of an experiment to investigate the impact of helicopter rotor blades on GPS signal reception. An offshore transport helicopter was equipped with a measurement system including a TSO-C129 compliant receiver and a custom research receiver. GPS signals passing through rotor discs of this aircraft were found to suffer a reduction in received signal strength, leading to potential navigation and RAIM availability concerns. The phenomenon will vary between installations and receiver types. Test procedures to identify the occurrence of the phenomenon in operational GPS installations are presented, together with possible in-service monitoring programs to assess the impact on the navigation function.

KEY WORDS

1. Helicopters. 2. Rotors. 3. GPS. 4. Safety.

1. INTRODUCTION. Since the demise of the VLF/Omega and Decca hyperbolic navigation systems the helicopter fleet supporting the UK offshore petroleum exploration and production industry has become exclusively reliant on GPS as a radio navigation aid. Since 1994 (CAA, 1994) GPS has been accepted for use in helicopters for en-route purposes in offshore operations and the helicopter fleet has been equipped with TSO-C129 and TSO-C129a certified receivers (FAA, 1992; FAA, 1996) in line with commercial fixed wing aircraft. However, there is clear potential for safety, operational and commercial benefits in the use of GPS to also provide approach guidance to offshore platforms. For several years, the Safety Regulation Group of the UK Civil Aviation Authority (CAA) has been conducting research to investigate the feasibility of using GPS and/or differential GPS (DGPS) for this application.

Analysis of the data collected during a campaign of CAA sponsored offshore approach flight trials (Howson *et al.*, 1997; Dodson and Stevens, 1997; CAA, 2000; CAA, 2003) indicated a potential problem with reception of GPS signals. Specifically the carrier-to-noise density ratio (CNR) of those signals reaching the antenna after passing through the tail rotor disc were reported by one of the receivers to be

Figure 1. Sikorsky S-76C trials airframe showing GPS antenna positions.

degraded by up to 12 dB-Hz. A 14·2% reduction in the availability of ranging measurements for satellites known to be healthy was also observed. For any navigation or approach aid employed in aviation, it is necessary to establish its performance in terms of accuracy, availability and integrity in order to confirm that it is suitable for the application. It was therefore considered essential to improve the understanding of this phenomenon in order to attempt to bound its impact on performance.

This paper presents the results of CAA sponsored ground trials to investigate the potential problem caused by helicopter rotors. The work was performed by Cranfield Aerospace Ltd., who were involved in the original offshore approach trials, and the CAA Institute of Satellite Navigation (ISN) at the University of Leeds. The first objective of the work was to determine if the previously observed effect of the rotors on the measured CNR could be reproduced using the same aircraft, receivers and antenna installation. The second objective was to employ a custom receiver to sample the received signal at a high rate, allowing the effect to be observed and studied at a low level within the receiver. The final goal was to assess the impact of the phenomenon on range precision and availability. Given the results of the tests the severity of the problem caused by helicopter rotors could then be assessed. Recommendations could then be made to the CAA for both GPS antenna installation procedures and for further RAIM based analysis to allow the impact on GNSS navigation aid performance for particular applications to be determined.

2. EXPERIMENTAL PROCEDURE.

The experimental procedure adopted for the ground trials shall now be presented in terms of the airframe, the GPS receivers and the test procedure.

2.1. *Trials airframe.* The rotor experiment was undertaken using the aircraft employed in the original offshore approach trials (Howson et al., 1997); a Sikorsky S-76C. Two active GPS antennas were temporarily installed on the helicopter in the positions shown in Figure 1. One was located at the top of the vertical tail adjacent to the tail rotor, replicating the antenna position which had been used for the previous flight trials. The tail rotor is located on the port side of the aircraft and rotates in a vertical plane displaced laterally from this antenna by approximately 450 mm. The tail antenna was above the plane of the main rotors. The second antenna was installed on the fuselage nose immediately forward of the cockpit windshield in a position underneath the main rotor disc. In this position the antenna was approximately 1500 mm below the plane of the main rotor. These antenna mountings allowed the effects of the main and tail rotors to be investigated independently.

Both the main rotor and tail rotor on the S-76C comprise four blades and rotate at a constant speed in flight. The nominal rotation speeds are 313 rpm and 1723 rpm for the main and tail rotors respectively. The interval between the passage of successive blades for the two rotors are approximately 48 ms for the main and 9 ms for the tail. The rotor speed data was a critical parameter in these trials, and was stored by the aircraft flight data recorder (FDR).

2.2. *GPS receivers.* Three different receivers were used for the trial. Two of the receivers ('Receiver 1' and 'Receiver 2') were commercial C/A-code units with twelve and eight channels respectively, and had been used in the earlier flight trials program. Receiver 2 was a TSO-C129 certified receiver, modified to accept differential corrections. The third receiver was a 20 channel combined GPS/GLONASS survey quality instrument, developed by the ISN for research purposes (Riley, 1992). The data from each of the receivers was recorded at a 1 Hz rate and included (in addition to the navigation solution information) a tracking status flag and a signal level indication for each receiver channel, with Receiver 1 and the ISN receiver also providing code and carrier observables. The ISN receiver included an additional feature which allowed 10 s time histories (snapshots) of the correlator data for a selected channel to be logged at a 1 kHz rate for subsequent analysis. The ISN installation included a rubidium frequency standard which the receiver employed as a highly stable frequency reference.

2.3. *Test procedure.* The rotor experiment was conducted in an unobstructed area of the manoeuvring apron at Aberdeen airport in Scotland. The aircraft's heading was varied periodically throughout the trials in order to attain predetermined aircraft orientations relative to the GPS satellite constellation. The majority of the testing comprised a series of rotor start/stop sequences in which the rotors were accelerated from rest up to their maximum speed. Following a period of constant speed operation (typically around 1 to 2 minutes, although some longer runs were also undertaken) the speed was then reduced back to zero. Each change of rotor speed was undertaken in two stages owing to the need to start or stop the two aircraft engines separately. These sequences were designed to investigate whether the GPS interference effects varied significantly with rotor speed.

3. TEST RESULTS

3.1. *Repeatability of observed CNR reduction.* The first objective of the trial was to determine if the previously observed reduction in received signal level was again evident. The three receivers were connected to the antenna on the tail rotor. The aircraft was manoeuvred to a heading such that the signals from three satellites were received through the tail rotor disc. An initial period with the rotors stationary was used to obtain nominal CNR data. A rotor start/stop sequence was then performed, before again returning to a rotors stationary period to record the nominal CNR level. Receiver 1 and the ISN receiver provide CNR estimates in units of dB-Hz, whilst Receiver 2 provides a dimensionless 'signal level' parameter, which is believed to be a measure of signal *amplitude*. The recorded signal levels for this test are shown in Figure 2 for one of the three satellites, together with the rotor speed.

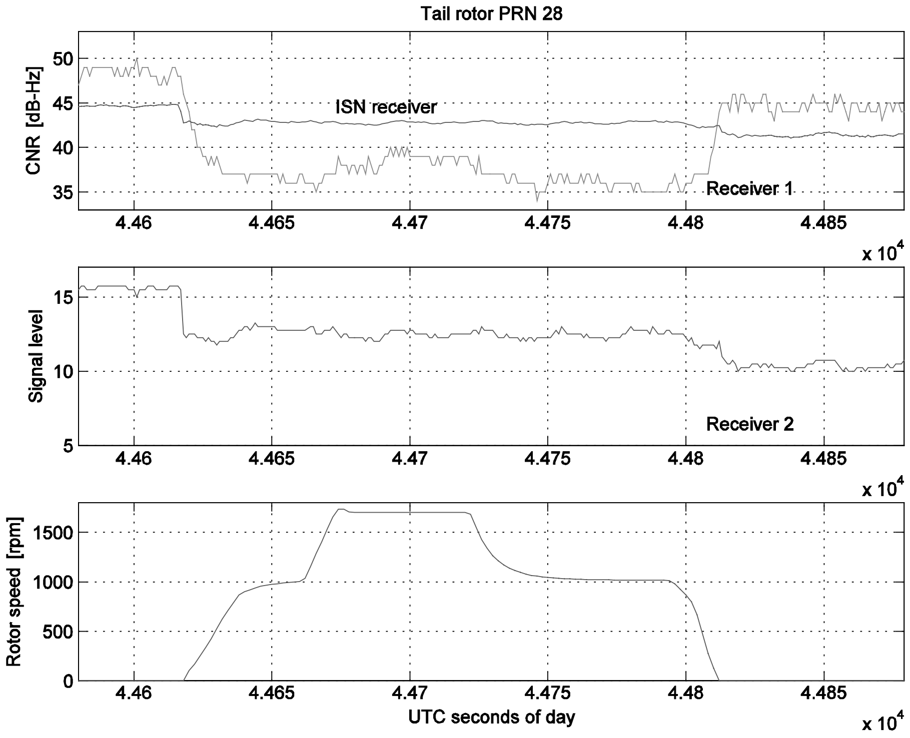

Figure 2. Measured CNR and signal level for three receivers.

It is clear that when the rotors are turning the received CNR or signal level estimates are reduced for all three receivers. Most prominent is the approximately 10 dB-Hz reduction reported by Receiver 1, which is of similar magnitude to the CNR reductions observed during the original approach trials with that receiver (up to 12 dB-Hz). The repeatability of the effect during this ground trial excluded the possibility of either aircraft dynamics or interference in the vicinity of the offshore platforms as the cause of the previously observed phenomenon. It should also be noted that the approximately 3 dB-Hz difference in CNR before and after this test is believed to be due to the different positions in which the blades came to rest, leading to different multipath conditions.

The CNR reduction reported by Receiver 1 is clearly greater than that for the ISN receiver, which shows a reduction of only 2 dB-Hz. In addition the signal level reported by Receiver 2 reduces by approximately 20% when the rotors are turning, which would equate to a CNR loss of approximately 1·9 dB-Hz if this parameter is indeed related to *amplitude*. The CNR reduction does not appear to vary significantly as a function of rotor speed. Further rotor start/stop sequences produced similar discrepancies between the received signal level estimates output by the three receivers. In addition the effect was also evident when the signals pass through the main rotor, as is shown for Receiver 1 for two different satellites (Figure 3). It was therefore necessary to identify possible reasons for the discrepancies between the three CNR estimates and subsequently to ascertain the impact of the CNR reduction caused by the rotors.

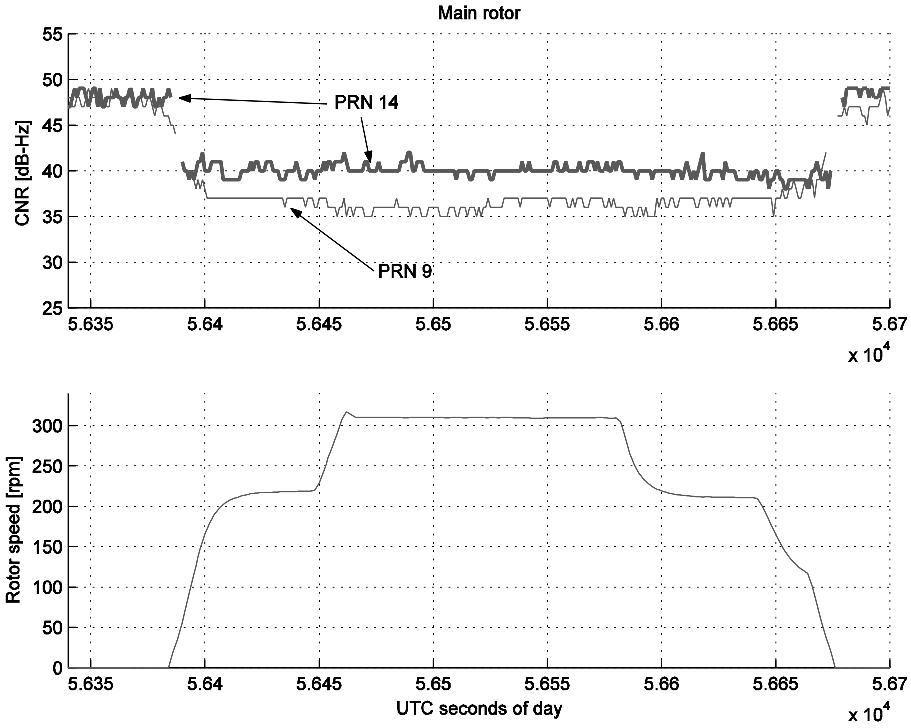

Figure 3. Receiver 1 signal level for main rotor test.

3.1.1. *Performance of CNR Estimators.* CNR estimates from a GPS receiver are based upon the correlator measurements made. The ISN receiver provided 10 s snapshot recordings of the in-phase and quadrature-phase punctual correlators (denoted I_P and Q_P respectively), at a 1 kHz rate. From this recorded correlator data it was possible to examine the behaviour of different estimation techniques with rotors both stationary and turning. This assessment was performed using two 'textbook' CNR estimators taken from the literature:

- 'Estimator 1' (Van Dierendonck, 1996) performs a comparison of the total signal-to-noise power in two different bandwidths using the I_P and Q_P data. For this analysis, 20 ms samples of the correlation data were used to generate the power estimates, and the results were averaged over 1 s to provide CNR updates at a 1 Hz rate.
- 'Estimator 2' (Spilker, 1977) is a technique applicable to one-bit quantized receivers, with known filter bandwidth. The technique generates CNR estimates based on summation of the I_P data over a specified interval. Summation over 1 s was used for this analysis to provide 1 Hz updates.

In addition a third CNR estimator, 'Estimator 3' was also examined. This is based upon *a priori* knowledge of the noise variance, σ^2. The CNR is estimated from the I_P and Q_P correlator totals according to:

$$CNR = 10\log_{10}\left(\frac{1}{T}\left[\frac{I_P^2+Q_P^2}{2\sigma^2}-1\right]\right) \tag{1}$$

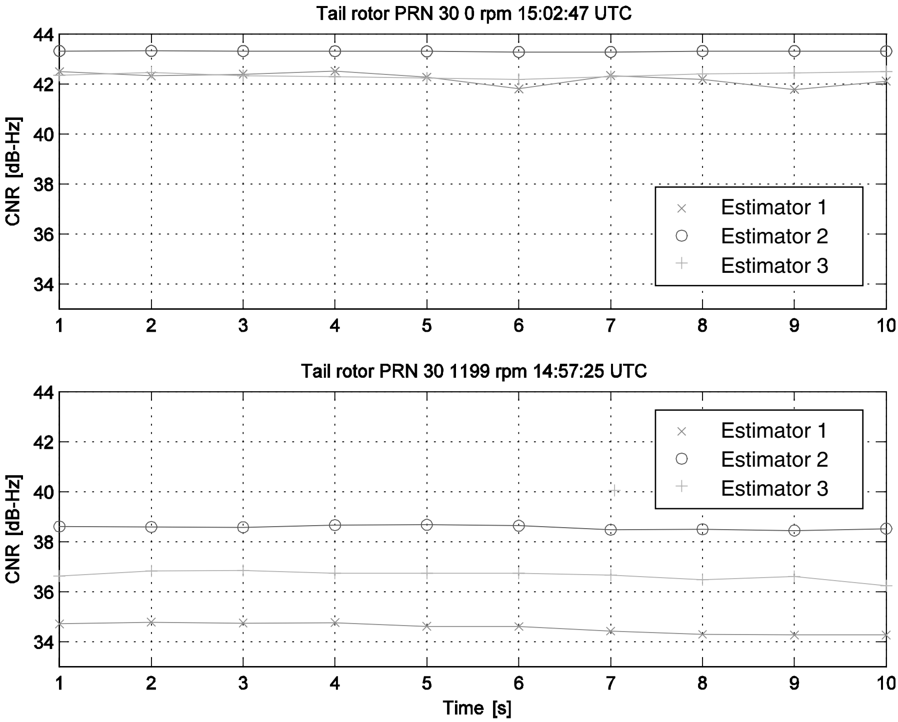

Figure 4. Performance of CNR estimators with rotors stationary (upper) and rotors turning (lower).

For comparison with the two 'textbook' estimators the 1 ms CNR estimates produced were averaged over the same 1 s period.

Figure 4 shows a comparison of the three estimator results obtained using two snapshot recordings from the tail antenna for the same satellite. The upper set of CNR data is for a period when the rotors were stationary, whilst the lower is for a period when the rotors were turning at a constant speed of 1199 rpm. From the upper plot it is clear that the three techniques produce very similar CNR estimates while the rotors are stationary, with 'Estimator 1' and 'Estimator 3' being almost identical. However, with the rotors turning the three estimators produce very different results with the average 'Estimator 1' values approximately 4 dB-Hz lower than those of 'Estimator 2' and 2 dB-Hz lower than those of 'Estimator 3'. This is a significant result as all three estimators are using exactly the same data. It is not possible to use this data to ascertain the exact amount of CNR reduction caused by the turning rotors, as the signal and multipath conditions cannot be guaranteed to be the same during the two tests.

The precise CNR or signal level algorithms employed by the two commercial GPS receivers are not known. However, it is significant that both in the actual data recorded from the receivers, and in the outputs from the off-line analysis using various estimators, significantly differing results were observed when the rotors were turning but not when the rotors were stationary. This suggests that caution must be used when interpreting a receiver's CNR output unless the specific estimation algorithm is

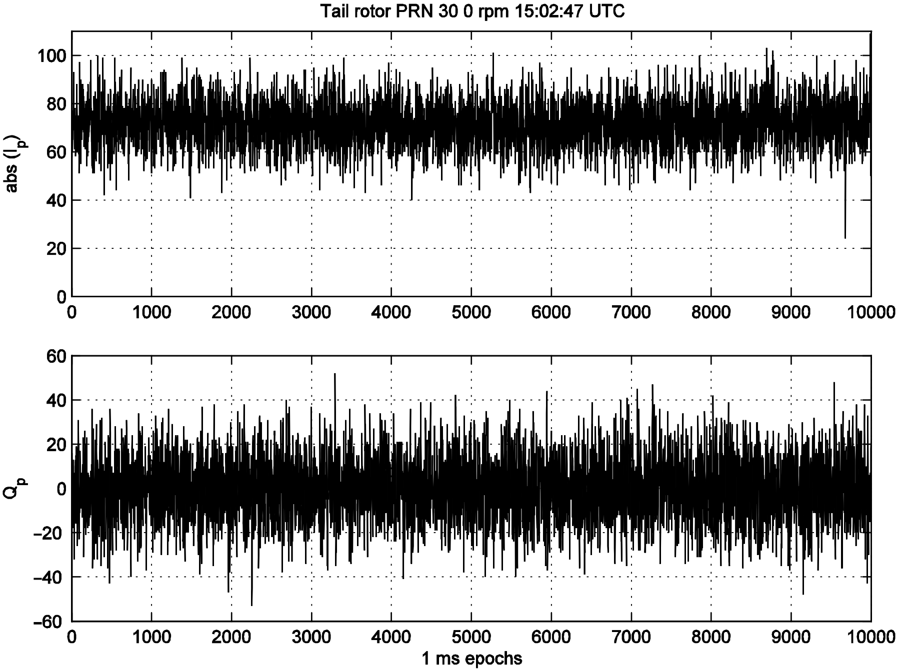

Figure 5. Snapshot correlation data with rotors stationary.

known. These results do not in themselves indicate which of the three estimation techniques is most accurate when the rotors are turning. In order to ascertain this it is necessary to examine the effect of the rotors on the received signal at the correlator level.

3.2. *Effect of rotors on signal-in-space.* The series of 10 s snapshots from the ISN receiver were employed to examine the effect of rotor blade passage on the received GPS signals. Figure 5 shows an example of an I_P and Q_P time domain plot based upon a period with the rotors stationary. The units of the vertical axes correspond to the scaled correlator totals used, which can be considered as scaled amplitude measurements. To improve clarity, the absolute value of the I_P correlator totals has been plotted in order to eliminate the phase transitions caused by the data message. This snapshot data is the same as that used in the upper plot in Figure 4 and is typical of that acquired with the rotors stationary. All of the signal energy is contained in the I_P channel with the Q_P data consisting only of zero-mean Gaussian noise.

Figure 6 represents the same data converted to the frequency domain by means of a discrete Fourier transform operating on the signal power quantity $P(t)$, defined as:

$$P(t) = I_P^2 + Q_P^2 \tag{2}$$

The frequency domain plot reveals a flat spectrum with the exception of the component at 0 Hz, which extends to a value of $7{\cdot}2 \times 10^5$ and is due to the non-zero mean of the power data, $P(t)$.

Figure 7 shows a 10-s snapshot collected with the rotors turning, for a satellite whose signal path to the antenna intersected the tail rotor disc. This is the same data

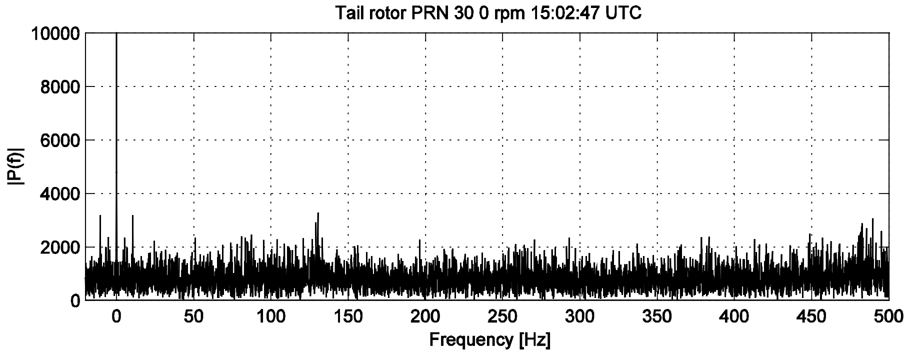

Figure 6. Frequency spectrum with rotors stationary.

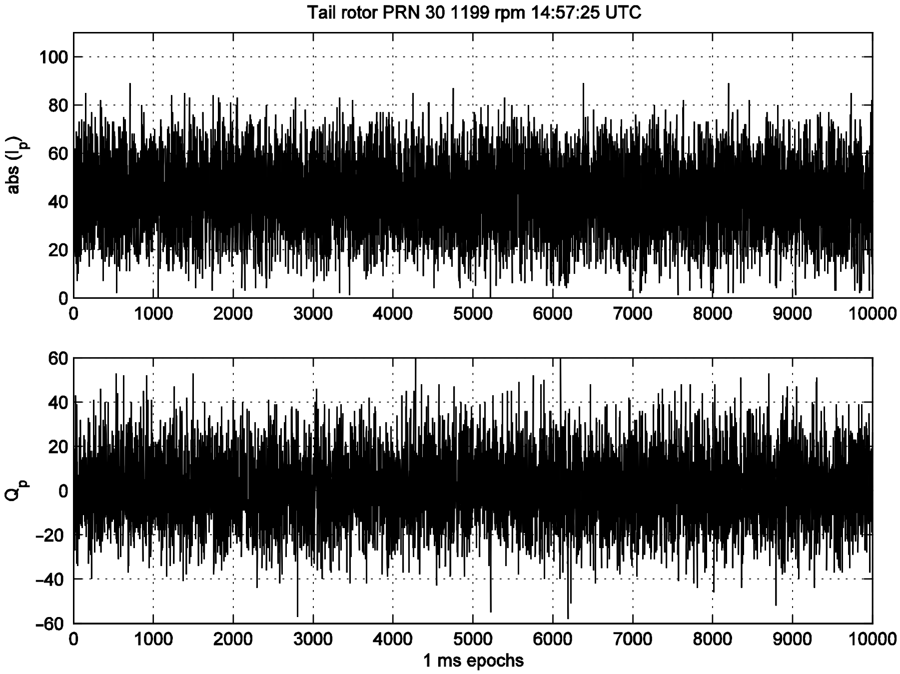

Figure 7. Correlation data with rotors turning.

that was used for the lower plot in Figure 4, which was recorded five minutes prior to that shown in Figure 5. Compared to the stationary data, it is apparent that the variance of I_P has increased significantly. Increasing the scale of the horizontal axis (Figure 8) reveals oscillations which appear to be associated with the passage of successive tail rotor blades. Each oscillation consists of a short period of reduced amplitude (approximately 50% of the steady-state I_P value) followed by a longer period where the amplitude returns to near the steady-state level.

Transformation of the 'rotors turning' data to the frequency domain (Figure 9) reveals a series of spectral lines, with a fundamental component at 81 Hz. Given the

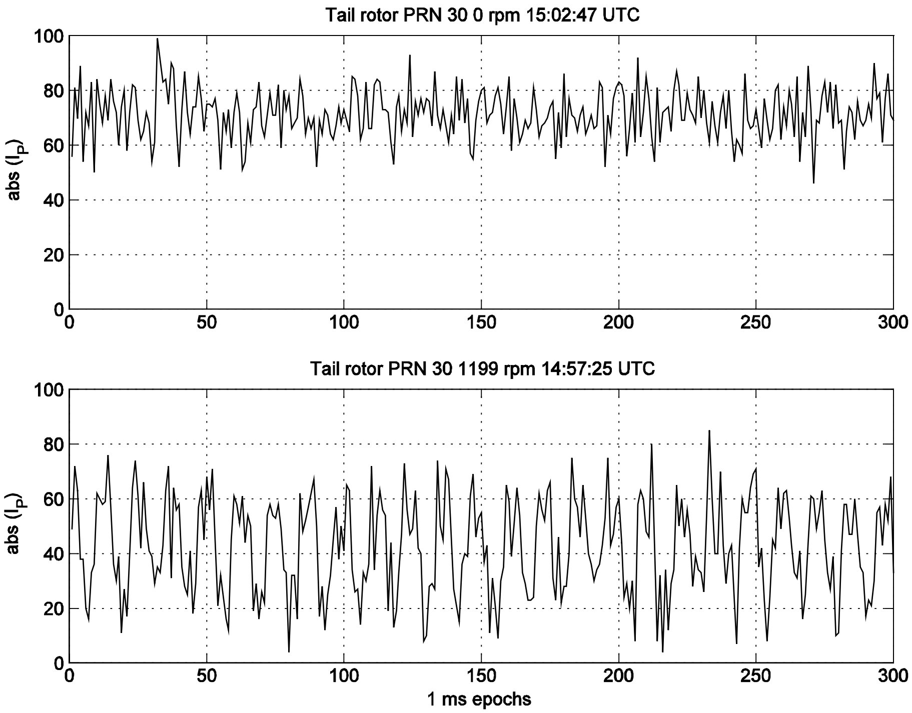

Figure 8. Comparison of correlation data with rotors stationary and turning.

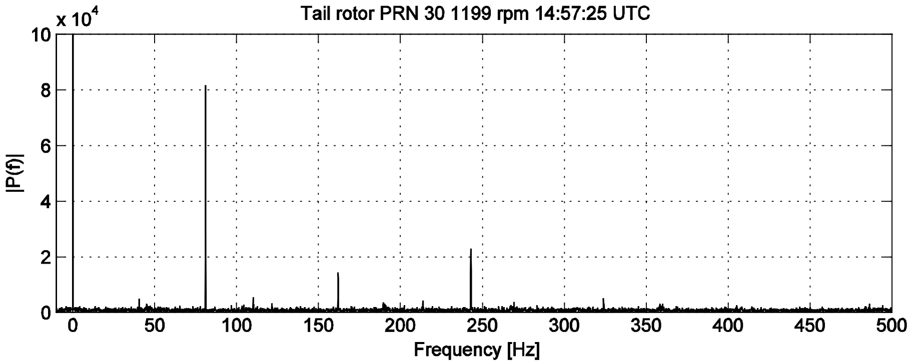

Figure 9. Frequency spectrum with rotors turning.

measurement accuracy of the rotor speed data (1%) there is very close agreement with the calculated blade passing frequency of 79·9 Hz (4 blades at 1199 rpm). Examination of other snapshot recordings for signals passing through the tail rotor revealed oscillatory effects similar to those shown in Figure 8. Changes in rotor speed, and thus the blade passing frequency, were observed to have a direct impact upon the frequency of the oscillations. A clear example of this is shown in Figure 10 during a period when a snapshot was taken while the rotor speed was reducing. The rotor

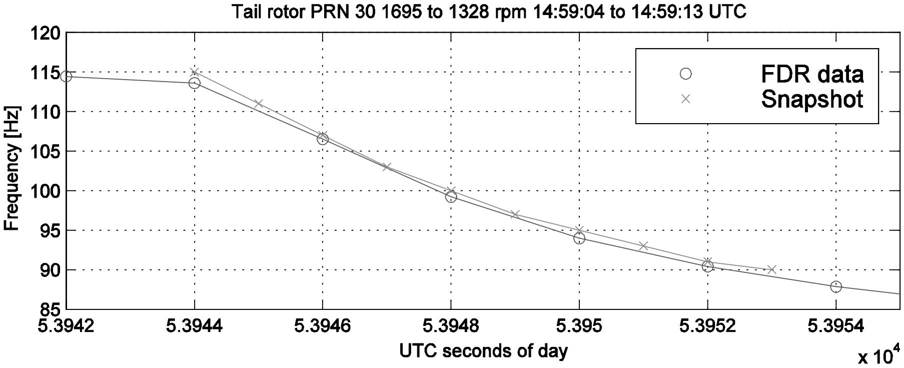

Figure 10. Fundamental oscillation frequency and rotor speed versus time. *P*.

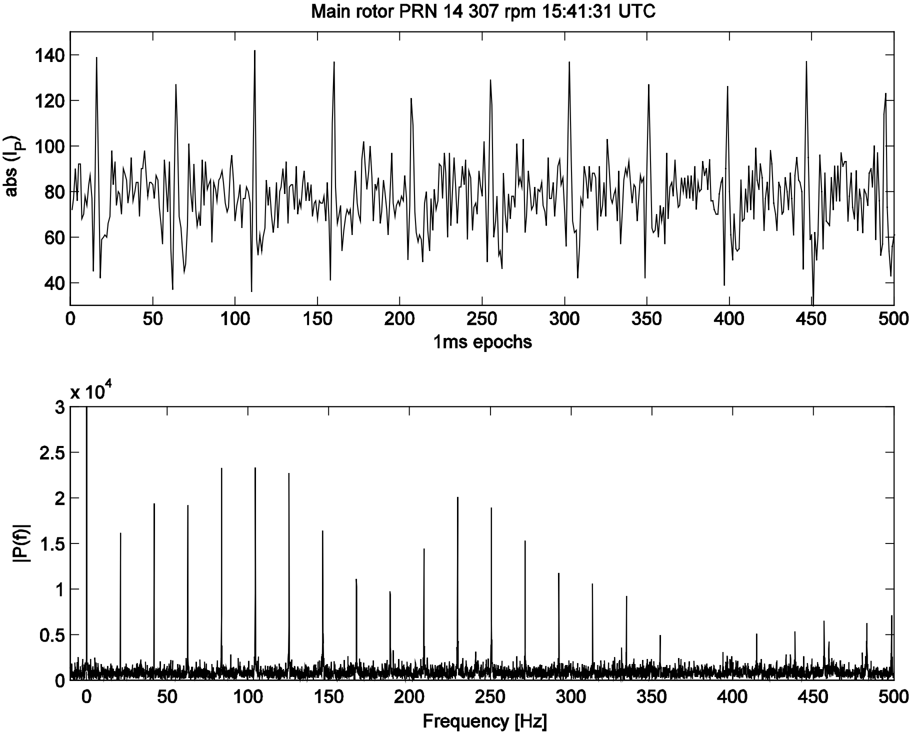

Figure 11. Correlation data and spectrum with rotors turning.

speed is labelled as 'FDR data', whilst the fundamental oscillation frequency is labelled as 'Snapshot'. Similar results were produced for other satellites.

The effect of the main rotor on the GPS signals was also assessed. Figure 11 shows snapshot data for a satellite whose signal path intersected the main rotor with a duty cycle of approximately 5%, whilst the rotors were turning at full speed. In contrast to the tail rotor, it appears that the passage of each main rotor blade results in a sequence of excursions in which the amplitude first reduces, then increases to a level considerably in excess of the steady-state value (approximately a 100% increase), followed by a second reduction before the signal returns to its original level. The frequency domain results reveal a very rich spectrum. However, the spectral component with the greatest amplitude is in this case at a *harmonic of* the blade passing frequency (21 Hz) due to the presence of the large amplitude excursions in the time domain data. This suggests that multiple effects, both destructive and constructive, were occurring as each blade passed in front of the antenna. Similar results were also observed in a second set of main rotor snapshot data recorded at a slower rotor speed.

During the tests it was also discovered that it was not always necessary for the signals to be propagating through a rotor disc in order for oscillations to be present. A similar effect was observed for a low elevation satellite on the opposite side of the aircraft to the tail rotor, suggesting that a multipath effect was present which varied dependent upon the angular position of the tail rotor. Only a small number of snapshots were available in the recorded data set for satellites in this position and so this effect could not be fully characterised.

3.2.1. *Estimation of rotor induced attenuation.* To determine which of the three CNR estimators presented previously is most accurate when the rotors are turning it was necessary to estimate the attenuation induced by the rotors. A simple model of the interference effect was devised to estimate the attenuation caused by the rotor blades. The tail rotor data was used, as opposed to the main rotor data, as the majority of the snapshot recordings were from the tail antenna. The signal power time histories $P(t)$ were approximated by a two-level square wave model in which the lower level corresponded to the reduced amplitude portion of each cycle, and the upper level to the steady-state power during the remainder of the cycle. A least-squares technique was used to obtain a fit between this model and the recorded data, with the ratio of the upper and lower power levels providing an estimate of the attenuation during the blade passage. The results obtained using this technique exhibited considerable variation between successive recordings which was attributed to the difficulties associated with modelling the noisy input data. A total of 39 snapshots (based upon data from two different satellites obstructed by the tail rotor, at elevations of between 24° and 36°) were analysed and the mean attenuation during passage of a tail rotor blade was estimated as 4·3 dB.

This estimation of the blade attenuation level allowed an assessment to be made as to which CNR estimator is most reliable when the rotors are turning. A controlled assessment was made using *simulated* correlator data which was generated for a given rotor speed and variable rotor blockage periods and variable CNRs. The attenuation level used was that predicted by the model for the data used previously in the lower plot in Figure 4. The CNR loss for the three CNR estimators is compared with the predicted loss in Figure 12. The predicted loss is based on the *average* power that would be available and is shown as a continuous line.

As can be seen both 'Estimator 2' and 'Estimator 3' produce losses that are very close to the predicted values, and crucially are independent of CNR. 'Estimator 1' clearly produces losses far in excess of those predicted, with a clear CNR dependence. Hence these results indicate that CNR estimators which are based upon simple averaging of the correlation measurements over time are better able to report the signal level when the rotors are turning. The use of signal-to-noise ratios in two

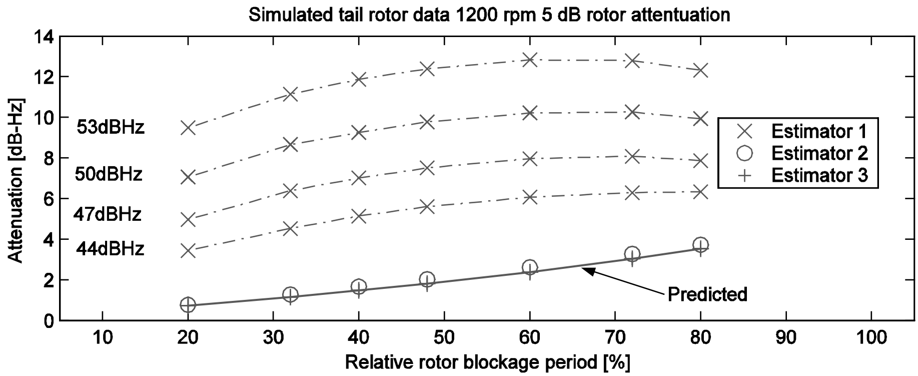

Figure 12. CNR loss for different CNR estimators.

different bandwidths for 'Estimator 1' appears to be adversely affected by the rotor attenuation effect.

3.3. *Effect of rotors on pseudorange precision.* The quality of the receiver's position solution is dependent on measurement accuracy, which includes ranging precision, together with satellite geometry. An analysis was therefore undertaken to investigate whether the rotor induced perturbations and consequent CNR reductions, had any adverse impact upon the precision of the ranging measurements. To investigate the effect of the rotors on pseudorange errors, a code-minus-carrier (CMC) evaluation was undertaken using data from Receiver 1. Similar data was not available from the outputs of Receiver 2, as the TSO-C129 standard does not mandate the provision of such data (FAA, 1992; RTCA, 1991). The CMC technique requires removal of the carrier phase integer ambiguity and, since only single frequency measurements were available, it was also necessary to remove the effect of the unknown ionospheric delay from the CMC data. For the relatively short time periods used it proved sufficient to achieve this by applying a quadratic fit.

Figure 13 shows a time history of the CMC results and rotor speed for a satellite whose signals were subjected to blockage by the tail rotor. Continuous carrier tracking was maintained on this satellite throughout three complete rotor start/stop sequences. For reference the effect of the second of these start/stop sequences on the CNR output of Receiver 1 was shown previously in Figure 2.

Examination of the data reveals that multipath effects (the oscillatory structures with periods of several tens of seconds or longer) were present throughout the period in question, and these were attributed to the airframe and the surrounding environment at the test site. There is no evidence in the figure for any significant increase in code tracking noise during the periods when the rotors were turning, and this was confirmed by analysing the first and second derivatives of the CMC data.

A similar analysis was undertaken for several other satellites subjected to blockage by either the tail or main rotors, and confirmed the lack of evidence for any discernable increase in code noise while the rotors were turning. The results suggest that, if any such error exists, it will most likely be below the sub-metre level and can therefore be considered to be negligible. This finding confirms in detail the general findings of the previous flight trials, which did not identify any significant degradation in position domain accuracy due to the airframe and rotors.

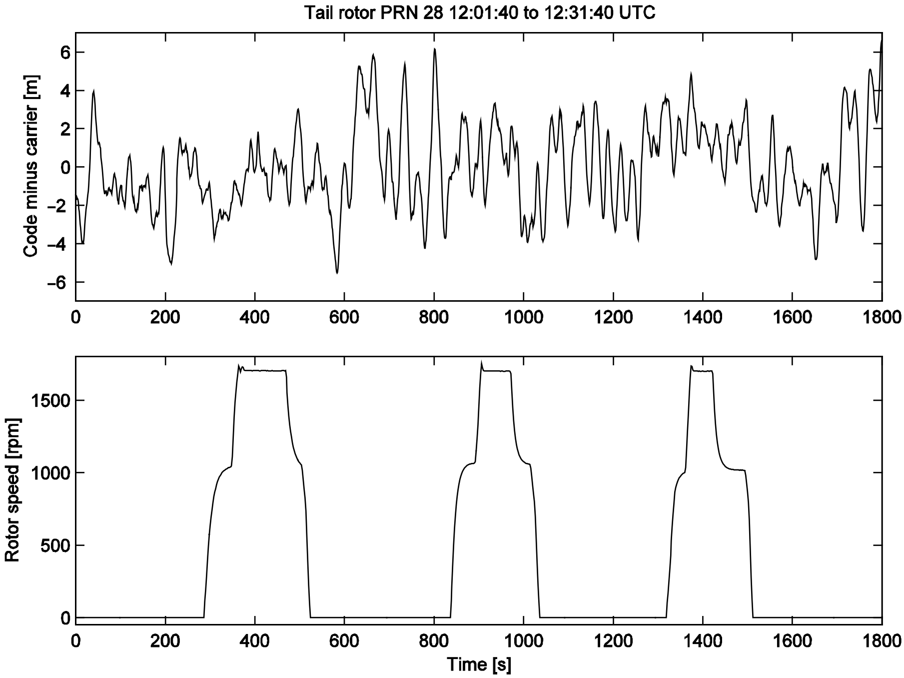

Figure 13. Code minus carrier for tail antenna during rotor start/stop sequences.

3.4. *Effect of rotors on range availability.* Although the results suggest that the impact of the rotors on the range measurement precision is negligible, it was also necessary to examine whether they caused any detrimental effect on the ability of a receiver to maintain continuous tracking of the satellite signals. This has potential impacts on the availability of both the navigation and RAIM functions. To perform this evaluation, time histories of the tracking status flags output by Receivers 1 and 2 during the rotor start/stop sequences were examined. The analysis did not consider the different tracking state indications (e.g. code lock, carrier lock, data demodulation) in detail, instead a satellite was treated as either 'available' or 'unavailable' dependent upon whether the receiver was capable of using the measurement in its navigation computation. This satellite tracking information is not a standard output required by the TSO-C129 standard (RTCA, 1991).

Figure 14 shows the ranging measurement availability results from a start/stop sequence using the tail antenna, with the solid horizontal lines indicating the presence of valid measurements from each satellite tracked. Examination of the data reveals that both receivers experienced loss of lock on several satellites during the period with rotors running. Receiver 1 is a 12 channel unit whereas Receiver 2 is an 8 channel, hence the two sets of results are not fully comparable. However, both receivers were attempting to track three satellites (PRN 7, PRN 8 and PRN 28) whose signals were obstructed by the tail rotor blades. In both cases the ranging measurements from two of these satellites were observed to be intermittent while the rotors were running. Calculation of the positions at which the signal paths from these satellites intersected the plane of the tail rotor determined that the satellite for which continuous tracking

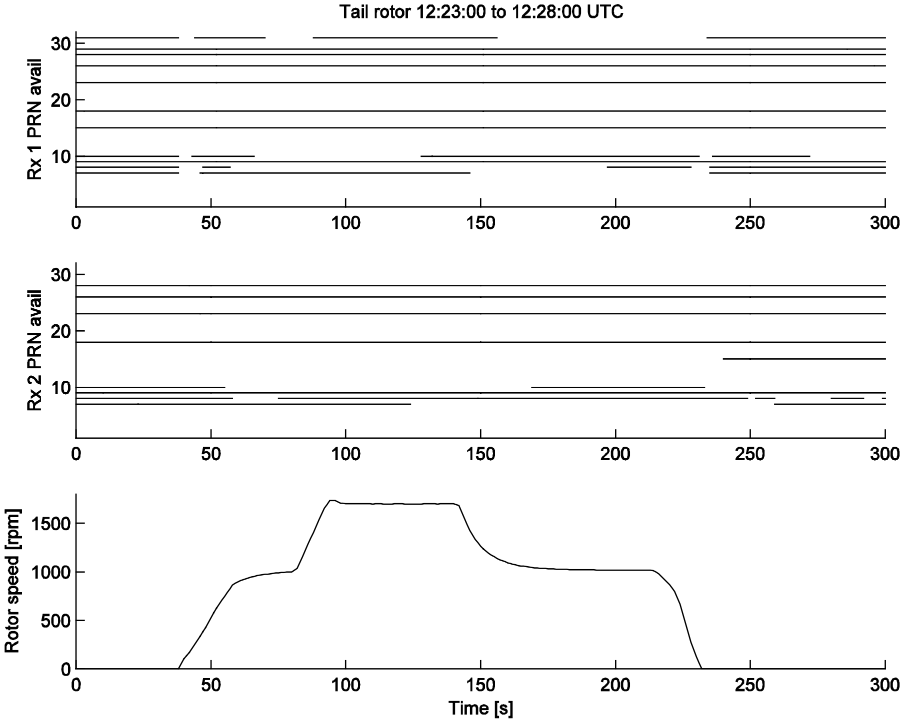

Figure 14. Ranging measurement availability for tail antenna during rotor start/stop sequence.

was maintained, PRN 28, was at a considerably higher elevation. Hence the nominal CNR for this satellite would be greater whilst the rotor blockage period would also be reduced.

Intermittent tracking while the rotors were running was also observed on two other satellites which, although not obstructed by the tail rotor, were both at very low elevations (6° for PRN 10 and 4° for PRN 31). This is consistent with the observation that satellites whose signals do not pass through the rotor disc can still be impacted by rotor induced interference/multipath effects.

Similar effects were observed on the other start/stop tests using the tail antenna, and a statistical measure of the effect on ranging measurement availability was computed in the form of a probability that a healthy satellite continues to be tracked by the receiver while the rotors are turning (Table 1). The results were obtained by averaging over all of the visible satellites irrespective of whether the rotor disc was obstructing the signal path, but with a mask angle of 10° applied to eliminate the lowest elevation satellites. These results show the ranging measurement availability to be reduced by a similar amount as was observed during the previous flight trials when the rotors were turning.

A similar availability assessment using data from the nose antenna revealed that the main rotor appeared to have negligible impact upon the receiver tracking performance. The test geometry was such that there were five visible satellites for which the signal path intersected the main rotor disc, plus a sixth satellite where the ‘pierce-point’ was at the edge of the disc. Receiver 2 did not lose any ranging measurements

Table 1. Ranging measurement availability probabilities observed for tail antenna.

Test Number	Sample length (s)	Receiver 1 range availability	Receiver 2 range availability
1	238	0·87	0·99
2	198	0·84	0·95
3	192	0·86	0·91
4	213	0·95	0·93
All tests	841	0·88	0·95

during the start/stop sequence whilst Receiver 1 was able to maintain continuous track at all rotor speeds above 29 rpm.

4. DISCUSSION.

The investigations reported here confirmed that when GPS signals pass through the discs formed by either the main or tail rotors, the effect of rotor blade passage is to introduce perturbations in the received signal, synchronised with rotor speed. There was a limited amount of evidence suggesting that it is also possible for perturbations to be present where the satellite signals arrive at the antenna from the opposite side of the aircraft to the tail rotor, due most likely to multipath propagation. The data gathered from the tail rotor indicated that each blade was causing an attenuation of the signal as its path was blocked. A simple modelling process was used to estimate the average attenuation level as 4·3 dB, resulting in an average CNR loss in the region of 1 to 2 dB-Hz when the blockage period is accounted for. This average CNR reduction is much smaller than that reported by Receiver 1, which indicated a reduction typically in excess of 10 dB-Hz. The effects of the main rotor on the received signal were more complex, comprising both reductions and increases in amplitude, and due to the more limited data obtained from the main rotor no effort was made to estimate its attenuation characteristics.

4.1. *Pseudorange precision.* Investigation of the effect of the rotors on pseudorange measurement precision revealed the impact to be negligible, despite the reduction in CNR. This is due to the nominal signal levels during these trials being relatively high, typically in excess of 40 dB-Hz, hence a 1 to 2 dB-Hz reduction in CNR has little impact on precision. However, for signals received at the minimum levels applicable to TSO-C129 and TSO-C129a certified receivers (RTCA, 1991), the errors could be larger if the code tracking is assumed to be non-coherent. Therefore in some high accuracy applications, such as precision approach and landing systems, the increase in code noise could represent a significant problem.

4.2. *Measurement availability.* Examination of the ranging measurement availability (determined using the receivers' channel tracking flags) revealed clear evidence of a reduction in performance which was correlated with the rotor motion. This effect was observed for two different receivers using the tail antenna and was most severe for signal paths which were obstructed by the tail rotor disc. Apart from some transient effects at very low rotor speeds, there was no evidence of any reduction in availability due to the main rotor.

Statistical analysis of the tracking performance data for the tail antenna revealed that, for one receiver, the reduction in the number of available ranging measurements was in excess of 10%. This statistic is a mean value calculated by averaging over several successive tests. To extrapolate from these results to determine the overall impact upon a GPS receiver's navigation function requires a detailed availability assessment, considering all of the different failure modes and environmental conditions including the effects of aircraft dynamics or attitude changes.

The ISN, in combination with Imperial College and Helios Technology Ltd., is currently performing a GPS failure modes and effects analysis for a number of aviation applications for the CAA. The results of the work reported here will be an input into this process when considering the case of helicopter operations.

An important factor that must also be considered within the frame of this work is that for the past several years, the performance of the GPS constellation has been in excess of that which is guaranteed to civilian users by the Department of Defense (DoD). The number of healthy satellites on orbit and the received signal power level have both typically been in excess of that specified by the DoD, with many satellites exceeding their on-orbit design lifetimes. As of November 2004, the current 30 satellite constellation includes 17 Block II/IIA satellites that are beyond their 7·5-year design life (Losinski, 2000). With fewer satellites available, or with reduced signal power, the availability reduction due to the rotor effects would almost certainly be greater. Before undertaking an availability assessment it would be important to identify the appropriate constellation performance assumptions to be employed for the analysis.

4.3. *Recommendations.* The results reported here were obtained using two specific antenna positions on a single type of helicopter. Therefore they serve only to indicate that a potential problem exists and must not be considered as a benchmark against which to compare other installations. Factors which are likely to influence the nature of the modulation include the construction of the rotor blades and the relative geometry between the antenna and the rotors. Currently there is very little in the way of guidance material to assist the avionics design engineer in the selection and validation of a suitable site to locate the GPS antenna, although the importance of the antenna installation is recognised (FAA, 1994).

If additional data is deemed necessary to quantify the impact of rotors on specific helicopters' GPS installations, then it is suggested that this might be better performed using empirical measurements rather than by attempting to model the effects theoretically. Assuming that any rotor-related problems are likely to manifest themselves as reductions in ranging measurement availability, then the goal of an empirical aircraft test should be to investigate whether there is any significant variation in the receiver's tracking performance for satellite signals originating from different relative positions.

One possible empirical method would be a rotors-running ground trial similar to that described in this paper. The trial would need to be designed such that data was collected from a representative sample of different signal directions, for example by performing the test over an extended time period (several hours or longer) to take advantage of the satellites' orbital motion.

An alternative approach for the assessment of existing GPS installations would be to perform an in-service measurement trial. Although not as controllable as a ground test environment, this would allow GPS performance data to be captured in an operational situation and would reveal the impact of all the different factors affecting receiver tracking performance (e.g. attitude changes, dynamics, vibration) in addition to any rotor-related effects. The CAA sponsors a helicopter operational monitoring programme (HOMP) (CAA, 2002) under which a number of offshore helicopters have been configured with data recording equipment. It has been suggested that this equipment could be modified to acquire data on the GPS receivers' performance for subsequent analysis.

The work performed here has indicated that availability is the only performance parameter to be significantly affected by the rotor blades. Therefore the suggested tests would involve monitoring of the receiver's RAIM availability flag; providing data on the availability of an integrity-assured position solution. The discrete RAIM status could be added to the flight data recorder data frame and monitored on a continuous basis via HOMP. As well as assessing current availability, this would also allow future availability to be monitored as and when the constellation changes.

This experiment identified the limitations in the use of the CNR outputs from existing receivers as an indicator of potential rotor interference. However, this information has the potential to provide a useful insight into the health and performance of the installation if a known CNR algorithm is employed. It is recommended that future aviation receiver standards mandate the provision of CNR as an output. From the results obtained in this work the averaging type of CNR estimator appears to provide the most accurate information.

5. CONCLUSIONS.

The results of this study, combined with those from the previous flight trials, indicate that helicopter rotor blades have the potential to disrupt the reception of GPS signals. There are many factors that could affect the impact of the blades and it was not the intention to explore all of them in this experiment. For the particular aircraft and installation examined in this work the tail rotor blades lead to a notable decrease in range measurement availability, although range precision was not significantly affected. The potential impact of this phenomenon on the availability and continuity of the GPS navigation function in safety critical operations suggests that antenna location may be crucial, depending on the requirements of the phase of flight under consideration.

Current airworthiness guidelines provide no information relating to the methods used to select and assess the performance of antenna locations onboard a helicopter. As a result it has been recommended that tests be developed to enable ground based evaluation of rotor effects to be determined for a particular aircraft, antenna and receiver combination. An operational monitoring strategy has also been suggested which would allow all factors that affect receiver tracking performance to be quantified.

The ground based test would require outputs in addition to those required of current certified aviation receivers to be made available. The operational monitoring tests would also benefit from detailed receiver tracking status information being provided by such receivers. It has been recommended that future aviation receiver standards should incorporate the provision of this information in a standard format. The use of common algorithms for calculations such as CNR should also be considered, as it has been shown here that different algorithms can produce wildly differing results, and so such receiver outputs must be treated with caution unless the specific algorithm used is known.

ACKNOWLEDGMENTS

The research presented in this paper was commissioned and funded by the Safety Regulation Group of the UK Civil Aviation Authority in response to recommendations from the earlier work on offshore approaches (CAA, 2000; CAA, 2003).

Special thanks must be given to Dave Howson, CAA research project manager, whose enthusiasm and support has been instrumental in commissioning and managing the entirety of the helicopter research discussed and referred to in this paper. Thanks are also due to the following individuals for their invaluable contributions to the helicopter testing: Ian Brooks at Cranfield Aerospace, Michael Daly at the ISN, Shaun Friel and Jim Renwick at CHC Scotia.

The authors also wish to record their gratitude to ARINC Engineering Services, LLC (AES) for permitting Jeff Stevens, who was previously responsible for the Cranfield Aerospace contributions to this research, to participate in this paper. AES was not involved in the work on which the paper is based and the contents of this material represents the views of the authors.

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